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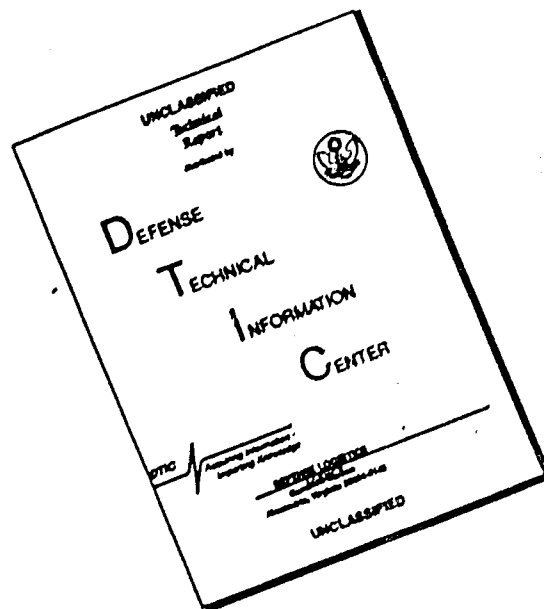
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**HEADQUARTERS
U S ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA 23604**

This report has been reviewed by the U. S. Army Transportation Research Command, and the results and conclusions are considered to be technically sound. The report is published for the exchange of information and the stimulation of ideas.

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May 1965

THE MARVEL PROJECT
PART E
A UNIQUE SOLUTION TO THE PROBLEM OF OBTAINING
TWO-DIMENSIONAL BOUNDARY LAYER DATA ON THE
VARIABLE-CAMBER HIGH-LIFT WINGS OF THE
MARVELETTE AIRCRAFT

Aerophysics Research Report No. 56

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to
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Symbols

δ	Boundary layer thickness, feet
θ	Momentum loss thickness, $\int_0^\infty u/u(1-u/u)dy$, feet
δ^*	Displacement thickness, $\int_0^\infty (1-u/u)dy$, feet
δ^{**}	Energy loss thickness, $\int_0^\infty u/u(1-u^2/u^2)dy$, feet
U	Local potential velocity
U_∞	Free-stream velocity
H	Boundary layer parameter, δ^*/θ
\bar{H}	Boundary layer parameter, δ^{**}/θ
U_τ	Friction velocity, $\sqrt{\tau_0/\rho}$, feet per second
τ_0	Surface shearing stress, pounds per square foot
ρ	Fluid density, slugs per cubic foot
ν	Kinematic viscosity, square feet per second

ABSTRACT

This paper reports on the design, construction, instrumentation and preliminary testing performed on the high-lift wing of the MARVELETTE aircraft in a two-dimensional wind tunnel. The wind tunnel, 12 feet high and 2 feet 9 inches wide, was fitted over a section of the aircraft wing to the shrouded propeller at the rear of the vehicle. When operating with this arrangement, wind tunnel velocities up to 60 miles per hour were obtainable in the test section. The tunnel provided more data in a few weeks of operation than would have been obtained in a number of months using a flight program with a considerable number of flights close to minimum flight speeds.

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INTRODUCTION

Aircraft which utilize distributed suction on the upper surface of the wings to suppress turbulent boundary layer separation, thereby attaining large lift coefficients, require detailed pressure distributions and boundary layer measurements at high angles of attack in the development stage of the high-lift system. The principal reason that an iterative technique is required is the inability of the existing potential flow theories to predict accurately the pressure distributions over airfoils at large angles of attack. Also, the prediction of the parameters of a turbulent boundary layer with distributed suction in severe pressure gradient is not an exact science.

To obtain this necessary aerodynamic data, it would seem obvious, especially with an aircraft capable of flight, that flight experiments were in order. However, when the flight test program is analyzed, it is obvious that a tremendous number of short flights would be required to obtain boundary layer profiles over the upper and lower surfaces of one station at one camber setting. When this is multiplied by the number of camber positions required, the cost in research time, not to mention financial outlay, would be quite extensive. Besides the above reasons against the measurement of boundary layer profiles on a high-lift wing in flight, another very critical variable that cannot be readily varied in flight, due to the emphasis on flight safety, is blower power. In the MARVELETTE, the main power plant and the blowers are mechanically connected; to reduce the blower power for a particular condition would require decreasing the thrust, which would mean that any measurements taken would be in the transient stage. Also, the easiest method of increasing the suction on a particular section of a wing would be to seal other parts of the wing so that the complete blower output is concentrated on the test section. However, the stability and control problems that would arise with this procedure immediately rule it out on the basis of safety. The addition of auxiliary blowers in the wings, etc., was considered; however, this would involve a major modification, and when this was considered in conjunction with the number of flights involved in the program, it was decided to consider other means of obtaining boundary layer measurements.

One possibility was that the aircraft be crated and shipped to one of the large wind tunnels capable of taking the complete aircraft in its test section; however, the cost of transportation, testing time in the tunnel, and personnel requirements would be undoubtedly very expensive. Another alternative of mounting the aircraft on a truck and driving at speeds of greater than 50 miles per hour was considered, although the difficulty of dealing with the tremendous thrust and lift forces from the aircraft would be considerable and the small length of

the large runway - 5000 feet - would make the testing time at each speed very small indeed. A solution to the problem was suggested by Dr. J. J. Cornish of the Aerophysics Department of Mississippi State University; his suggestion seemed to fulfill all the requirements for obtaining accurate boundary layer data and is also inexpensive and safe. A relatively small two-dimensional tunnel was built over a test section on the cambered portion of the wing; the rear shrouded propeller of the aircraft was utilized as a primary power plant for the tunnel as well as for the blowers. This tunnel was quite high in order to minimize downwash effects, and the flow was steady to allow steady-state conditions to exist. The capability of changing both the camber angle and the angle of attack of the airfoil was incorporated for a versatile experimental arrangement.

This paper reports on the design, construction, instrumentation, and preliminary testing performed on the high-lift wing of the MARVELETTE aircraft in such a two-dimensional wind tunnel.

DESCRIPTION OF THE TEST FACILITIES

A. MARVELETTE Aircraft

The MARVELETTE aircraft is a research vehicle intended primarily as a test bed for the MARVEL configuration. The aircraft has a tapered cantilever wing with conventional ailerons and a camber-changing capability behind the wing spar and inboard of the ailerons. A high-lift boundary layer control system is incorporated in the wings, which sucks the boundary layer air through small holes in the upper surface of the wings; this air is used to cool the engine, which is buried in the fuselage of the aircraft. The aircraft has a shrouded propeller to increase the total thrust at low forward speeds, and the conventional directional and longitudinal controls are an integral part of the shroud. Fiber glass construction provides the necessary aerodynamic smoothness for low drag operation in the cruise condition. A more complete description of this aircraft can be obtained from Reference 1.

B. MARVELETTE Wind Tunnel

To minimize ground effect due to the considerable downwash from the wing at large lift coefficients, it was necessary to build a high test section with sufficient width so that over the 5-foot chord of the test section, the disturbance from the walls would not interfere with the measurements taken aft of the trailing edge of the airfoil. From Reference 2, it was found that the average velocity through the shroud in the static condition was 120 feet per second; therefore, assuming a 30-percent loss in efficiency due to the presence of the tunnel, it was estimated that a test section 12 feet high and 2.5 feet wide would give a velocity through the test section of approximately 80 feet per second, which would be more than adequate for the tests.

The aircraft was moved to a position so that the tail pointed toward a section of the hangar door that could be opened during the tests. The wheels were removed and the aircraft was jacked into position, as shown in Figure 3, such that the uncambered airfoil section was approximately 7 feet above the ground. This was done so that when the wing was in the cambered position, adequate clearance between the trailing edge of the airfoil and the tunnel floor was provided. Sufficient tie-down points were cemented to the floor to control the thrust and pitching movements that would be generated by the propeller. The jacks upon which the aircraft was mounted were adjustable so that the angle of attack of the aircraft could be varied.

The construction methods and techniques used in building the wind tunnel can be clearly seen in Figure 4. The tunnel floor was constructed

from 3/4-inch plywood to withstand the weight of personnel, and most of the tunnel walls and ceiling were 1/4-inch plywood. All the curved surfaces consisted of 1/4-inch plywood bent around fir frames. All flat unsupported surfaces were braced with fir stiffeners, and a door aft of the test section trailing edge was cut in the side to allow for tunnel entry. Filler pieces curved to the shape of the wing in various camber positions were cut and assembled in such a way that the wing camber could be changed within minutes. Windows and lights were also provided to enable flow visualization studies to be performed. The vertical walls of the test section diverged slightly in a downstream direction, i.e., 1/2 inch in 5 feet, to allow for boundary layer development on the tunnel walls. The section where the tunnel wall intersects the fuselage and also the wall in the plane of the propeller were constructed such that if any angle of attack change were required, either the insertion or removal of rectangular strips would accommodate the change without any alteration of the contour portions of the wall. All the vertical corners in the tunnel inlet were constructed as portions of a 4-foot circular arc.

C. Calibration and Preliminary Testing of Wind Tunnel

Flush static pressure holes were inserted in the sides of the wind tunnel at the same level as the wing section, far enough in front so as not to be affected by the leading edge stagnation region. These static holes, together with the total head Kiel tube mounted in the wind tunnel, and an air speed indicator constituted a satisfactory air speed system. A number of static holes were made at various positions in the front part of the tunnel, and the air speed results were compared at a constant throttle setting by using a sensitive Kollsman helicopter air speed indicator and a Kiel tube in the center of the tunnel. From this survey, it was found that the static pressure taps in a region 3 feet in front of the wing section gave reasonably accurate air speed readings of the wind tunnel center-line velocity.

Initially the wind tunnel was designed so that the propeller removed air from a chamber, but this was found to be very unsatisfactory due to velocity fluctuation and flow surges caused by the flow into the propeller plane. To overcome this problem, the circular corners aft of the test section were removed and replaced by a curve, which, together with a central turning vane, insured a curved diffuser aft of the airfoil section trailing edge with an expansion angle of 6 degrees. The rounded leading edge of the central turning vane was 2 feet aft of the wing trailing edge, and the trailing edge of the turning vane, which ended at the fuselage, had an additional metal vane which directed the flow into the propeller. The above modifications to the wind tunnel eliminated the flow surges, and steady conditions

prevailed up to a wind tunnel center-line velocity of 60 miles per hour. A diagram of the tunnel can be seen in Figure 5.

Small woolen tufts were attached to the walls of the tunnel, including the inlet, to determine if any flow separations occurred at any of the commonly used throttle settings. Early in the morning or late in the evening when the wind was zero, the flow in the tunnel was very steady; however, when the wind rose above 3 miles per hour from certain directions, propeller surging occurred, which prohibited quantitative measurements. The tufts on the wind tunnel inlet during the velocity fluctuations showed intermittent regions of flow separation. The wind tunnel inlet design was found to be inadequate for its intended function when smoke from smudge pots revealed a tremendous amount of recirculation in the external flow pattern of the tunnel. The addition of curved metal plates to the inlet helped relieve this condition somewhat, but propeller surge was still prevalent. Open bleed holes in the tunnel at the downwind side of the fuselage opposite the propeller (see Figure 6) helped to suppress a lot of the propeller surges and raised the critical wind speed to 6 miles per hour. Due to the critical wind conditions and the noise produced by the wind tunnel operating in the hangar, all testing was restricted to early morning.

The engine oil in the MARVELETTE aircraft is cooled by the air from the boundary layer control system, supplemented by a small ram air duct in forward flight. Due to the excessive ground running required in the wind tunnel program, the oil cooler was inadequate for the task, and a large oil tank was added in series to the system; this increased the oil capacity by a large amount, thereby increasing the time required for the oil to reach maximum safe temperature. This solution to the oil-cooling problem required forced cooling of the oil tanks with large axial blowers between tests.

A horizontal piece of streamlined tubing on which eight Pitot-static systems were mounted at 4-inch intervals was used to calibrate the wind tunnel. Each Pitot-static system was connected to a sensitive Kollsman air speed indicator. The horizontal piece of streamlined tubing with flat end pieces was constructed so that it could be attached easily to the inside walls of the wind tunnel by means of adhesive tape, thereby making it easily adjustable in the vertical direction (see Figure 7). The velocity distributions in the test section of the wind tunnel are plotted in Figure 8.

D. Pressure Distributions

As the tunnel was assembled around the section of the wing that

had flush fitted pressure taps, pressure distributions were easily obtained by connecting tubes from the pressure taps to a photographic multitube water manometer (see Figure 9). This manometer had the capability of recording 52 separate pressure readings. A wide-angle lens was used on a 35-millimeter camera which was in the plane of the two banks of manometer tubes opposite a front surfaced mirror. The use of the mirror enabled the manometer configuration to remain relatively small for possible future use in aircraft.

The pressure distributions obtained at various wind tunnel speeds for each camber setting for a certain pitch angle of the aircraft are plotted in Figure 10.

E. Boundary Layer Measurements

Time-average boundary layer velocity profiles were obtained at various chordwise positions on the airfoil section by means of a multitube boundary layer mouse and a photographic water manometer. Figure 11 shows a boundary layer mouse used in these tests. The boundary layer velocity profiles were plotted; and the displacement thickness, momentum loss thickness, and boundary layer parameter (H) were calculated for each profile and plotted in Figures 13, 14, 15 and 16 respectively. Occasionally, when the boundary layer was thin and when very accurate measurements were required, the total head tubes from the boundary layer mouse were connected either to sensitive air speed indicators or to an inclined water manometer. Alternatively, a Pitot and a static tube, mounted on a platform which could be raised above the surface by means of a screw and a small electric motor, which automatically read on a remote meter the height of the Pitot above the surface in thousandths of an inch, were used for detailed movements. The Pitot-static system was connected to a Kollsman air speed indicator, and to insure that the total head probe just touched the surface, an electric circuit was wired from the total head through a battery and a light bulb to a small quantity of metallic paint on the surface of the airfoil. Thus, when the total head probe just touched the airfoil surface, an electrical circuit would be completed and the bulb would light. This technique for zeroing the probe eliminated any wind effects on the instrument. Figure 12 is a photograph of this boundary layer measurement system.

F. Flow Visualization

The flow in the wind tunnel during the preliminary testing and calibration was visualized by means of tufts on the walls of the tunnel, on the tunnel inlet, and on the shroud around the propeller. The flow

in the hangar around the wind tunnel was also visualized by means of smudge pots and flow patterns obtained by means of chalk marks on the floor of the hangar.

To observe if the flow on the upper surface of the airfoil section was attached, tufts were fixed at various chordwise stations, and photographs were taken of them at various tunnel speeds and camber settings. Typical photographs can be seen in Figure 17. From the pressure distributions on the test section, it appeared that at certain camber settings a laminar separation bubble was appearing on the leading edge of the section, and attempts were made by sublimation techniques to visualize the laminar separation bubble on the leading edge of the test section. The sublimation technique is explained fully in Reference 3. Briefly, it consists of spraying a saturated solution of naphthalene in petroleum ether onto a dark surface, and when the air moves over the section, flow patterns are observed and recorded. In a laminar separation bubble, the surface shear would be very low; thereby, the naphthalene in this region should remain on the section.

DISCUSSION OF RESULTS

The wind tunnel operated quite successfully, with relatively smooth flow conditions prevailing, after the modifications to the diffuser splitter plate and the wind tunnel inlet were incorporated. The addition of the large oil tank in series with the normal oil tank in the aircraft increased the ground running time at high throttle settings to 20 minutes prior to engine overheating. Between runs, forced cooling was performed by opening the cowlings and blowing cold air over the engine and oil tanks by means of a large-capacity axial blower. The vibration level in the tunnel was quite low except at the power settings above 90 percent, where partial propeller stall created considerable vibration and small flow surges in the wind tunnel. However, by keeping the power setting below about 90 percent, the vibration and fluctuation problems were minimized, and adequate flow was obtained in the wind tunnel. Additional stiffeners had to be attached to the 12-foot sides of the tunnel, since velocities of 50 miles per hour were adequate to suck the walls inward by a considerable amount.

The velocity distributions in the wind tunnel obtained during the calibration runs are shown in Figure 8. Although these show quite clearly that velocity gradients occur in the test section, in the region of the airfoil section there is a maximum velocity difference across the tunnel of only 2 miles per hour, which is quite reasonable if the relatively crude design of the tunnel is considered. The flow in the upper half of the wind tunnel is considerably faster than that at the bottom, and this is probably the result of two contributing factors: (a) the propeller being located in the upper half of the tunnel and (b) the influence of the wing in the tunnel in accelerating the flow in the upper section. Nevertheless, even though small pressure gradients existed in the test section, the flow was considered to be sufficiently homogeneous to give adequate aerodynamic data on the airfoil section within the normal range of experimental error.

The typical velocity distributions shown in Figure 10 are the result of a number of readings taken at different times. The velocity distributions were repeatable to within a few percent in all cases. The separation occurring at 50-percent chord is clearly defined from these velocity distributions, where pressure recovery occurs and considerable loss of lift is experienced. It is clearly seen that the boundary layer control system was not functioning properly, and it was probably due to a number of contributing causes such as a laminar separation bubble on the leading edge, insufficient blower power, or the porosity starting too far aft on the upper surface of the wing. To check out the insufficient blower power theory, an auxiliary blower

was added to the wing tip. It was found that this did not cure the separation problems; therefore, it was hypothesized that either a laminar bubble or insufficient porosity at the leading edge was the cause.

Some indication of the presence of a laminar separation bubble was found from certain pressure distributions where very low readings occurred at a certain pressure tap indicating flow separation. This was not due to stoppage in the tap, because for different camber settings the velocity drop moved to other static positions at the leading edge. Sublimation photographs failed to detect this bubble, which must have been very narrow; however, by careful measurements with Preston shear meters, a very small laminar bubble was found. From the above consideration, it was decided that, due to the presence of the laminar separation bubble and also to the fact that suction did not start until approximately the 12-percent chord position, the turbulent boundary had built up to such an extent that suction was not able to prevent the turbulent boundary layer separation in the severe adverse pressure gradient. An increase in leading edge radius and the addition of suction porosity to approximately the 2-percent chord position would prevent the laminar separation bubble from occurring and, consequently, would control the turbulent boundary layer and trailing edge separation.

The typical chordwise varieties of boundary layer parameters plotted in Figures 14 through 16 verify the presence of the thick boundary layer and the separation at the 50-percent chord position.

CONCLUSIONS

The wind tunnel built to obtain airfoil data on the high-lift wing of the MARVELETTE aircraft, which utilizes the aircraft propulsive system to drive the tunnel, performed very satisfactorily and gave adequate air flow to simulate flight conditions. The tunnel provided more data in a few weeks of operation than would have been obtained in a number of months using a flight program with a considerable number of hazardous flights close to minimum flight speeds. The problems with the tunnel such as engine cooling and flow fluctuations required considerable time to correct. Nevertheless, when the cost of building the wind tunnel and the cost of ground operations is compared with the cost of the equivalent flight operations required to give the same data, the wind tunnel could be considered to be very successful. The safety aspects of this type of operation on experimental wings must not be overlooked. The wind tunnel tests showed quite clearly that a laminar separation bubble existed at the leading edge of the airfoil and that, together with insufficient suction at the leading edge to control the relatively thick turbulent boundary layer, separation occurred at the 50-percent chord position for the 20- and 30-percent camber settings. Although the results were strictly two-dimensional, this is not thought to be a serious limitation when relative costs and safety are considered.

In future wind tunnels of this type, it would be preferable to have the tunnel separated from the aircraft propulsive system so that the curves just aft the test section could be eliminated with the propeller in the center of the section. Careful design of contraction, curves, inlets, etc., could give good flow conditions for two-dimensional testing of airfoil sections attached to aircraft.

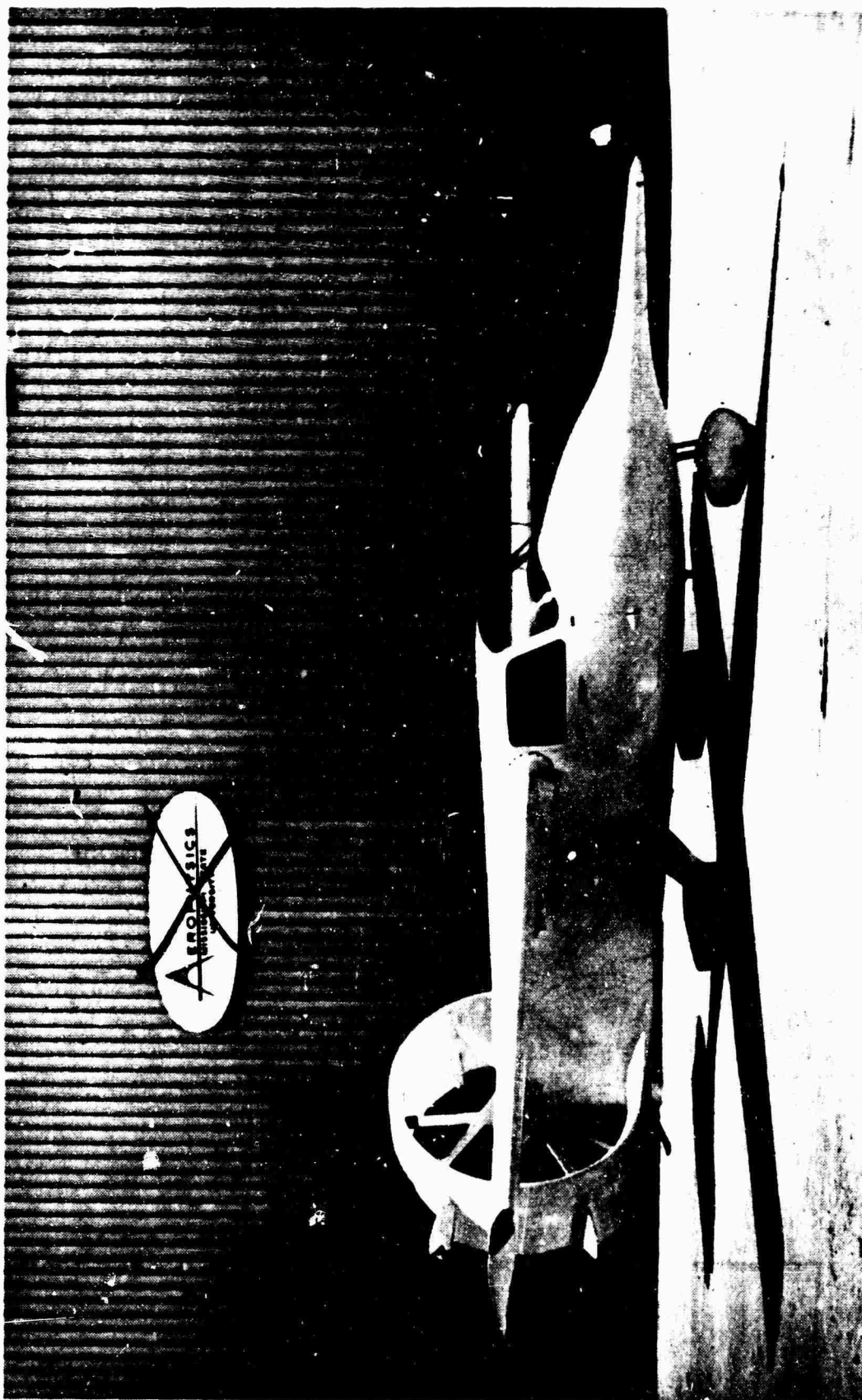


Figure 1. MARVELETTE Research Vehicle with Variable-Camber High-Lift Wings.

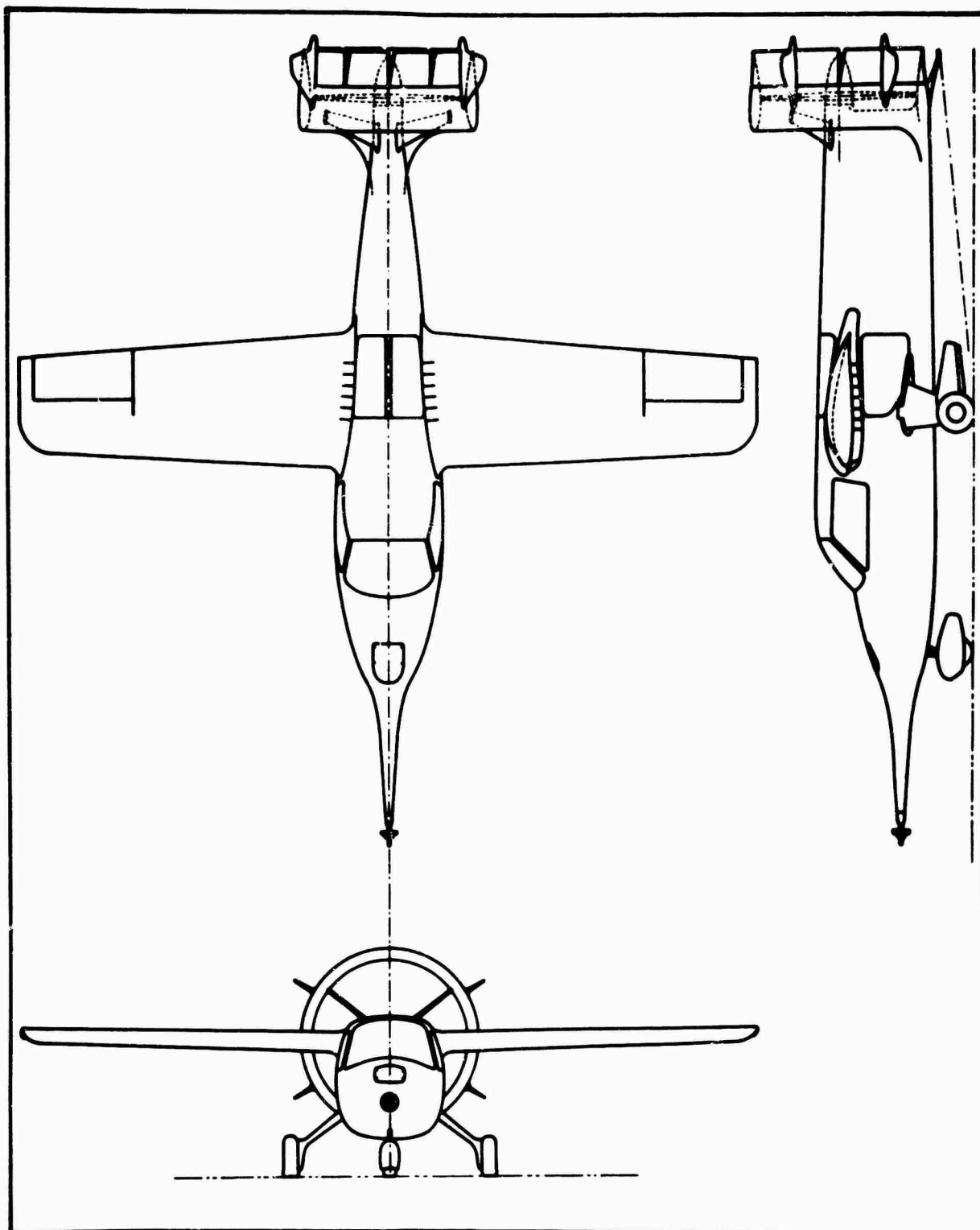


Figure 2. Three-View Drawing of MARVELETTE Aircraft.

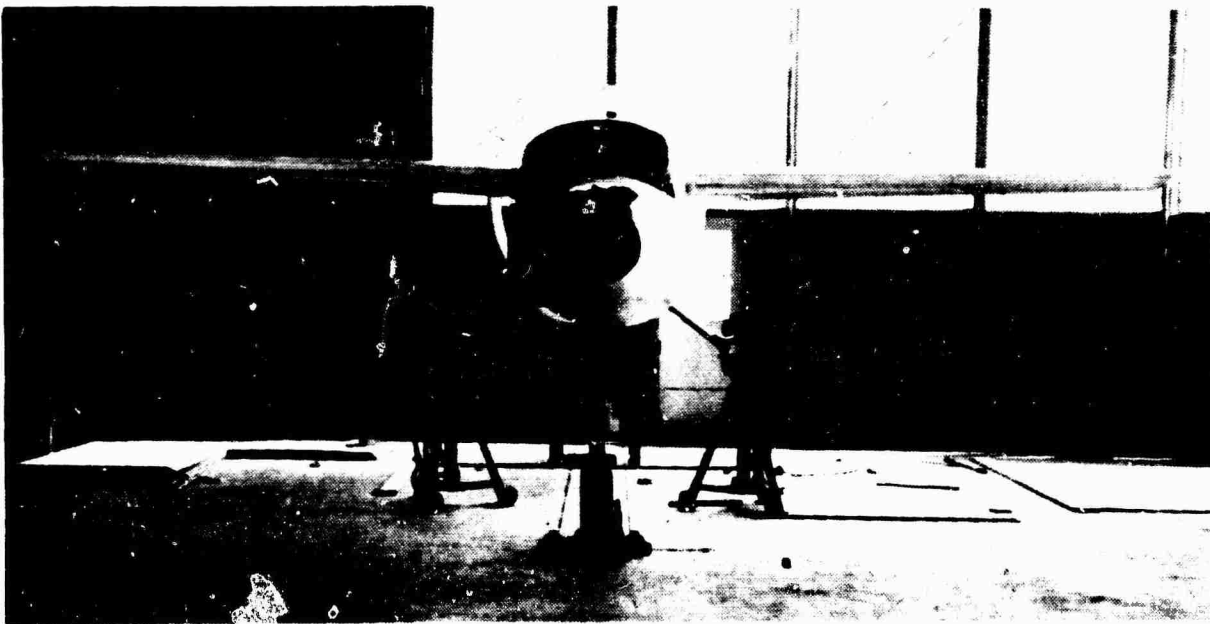
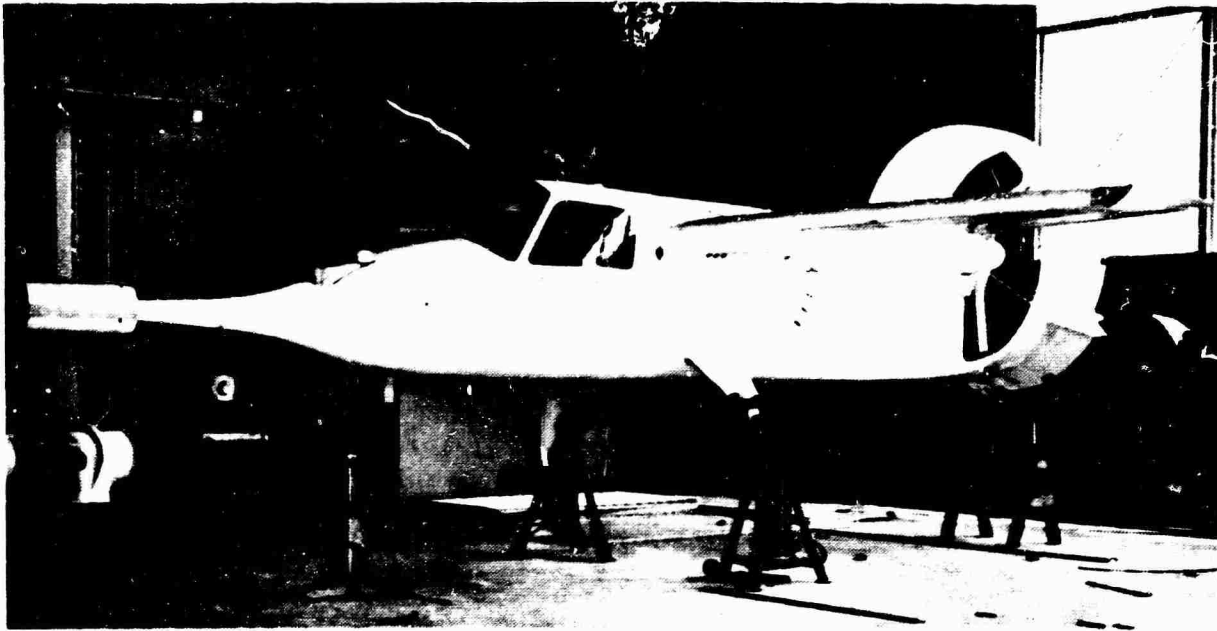


Figure 3. The Tie-Down Arrangement of the MARVELETTE Aircraft Prior to Building the Wind Tunnel.

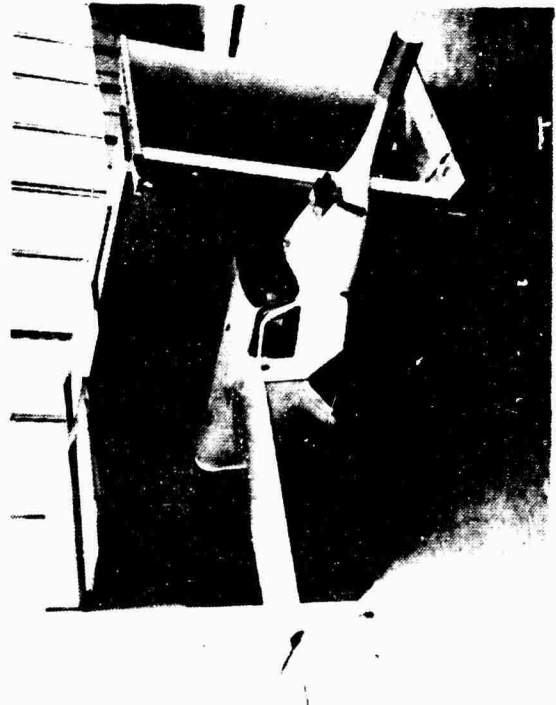
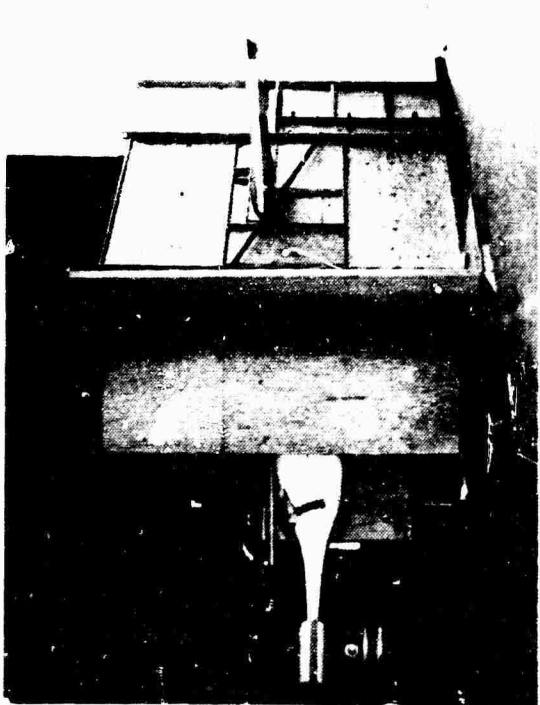
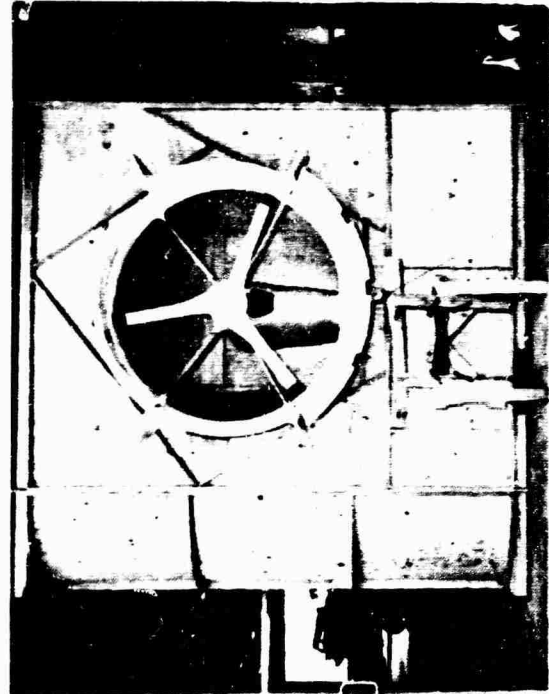
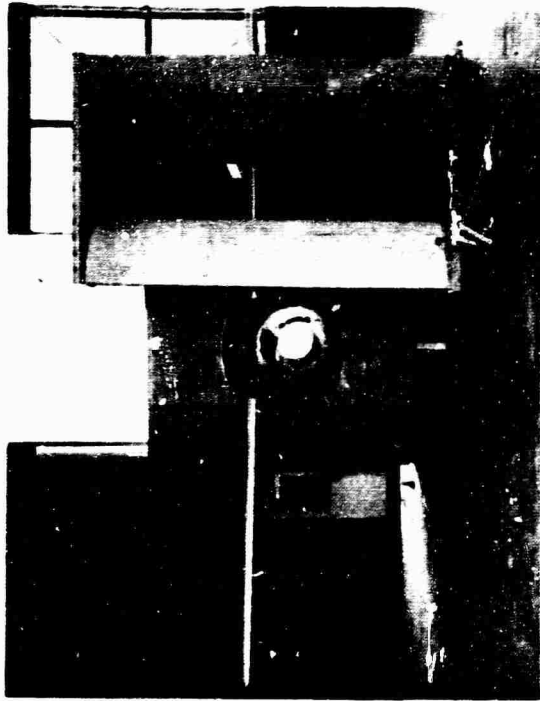


Figure 4. View of the Construction Techniques Used in Building the Wind Tunnel.

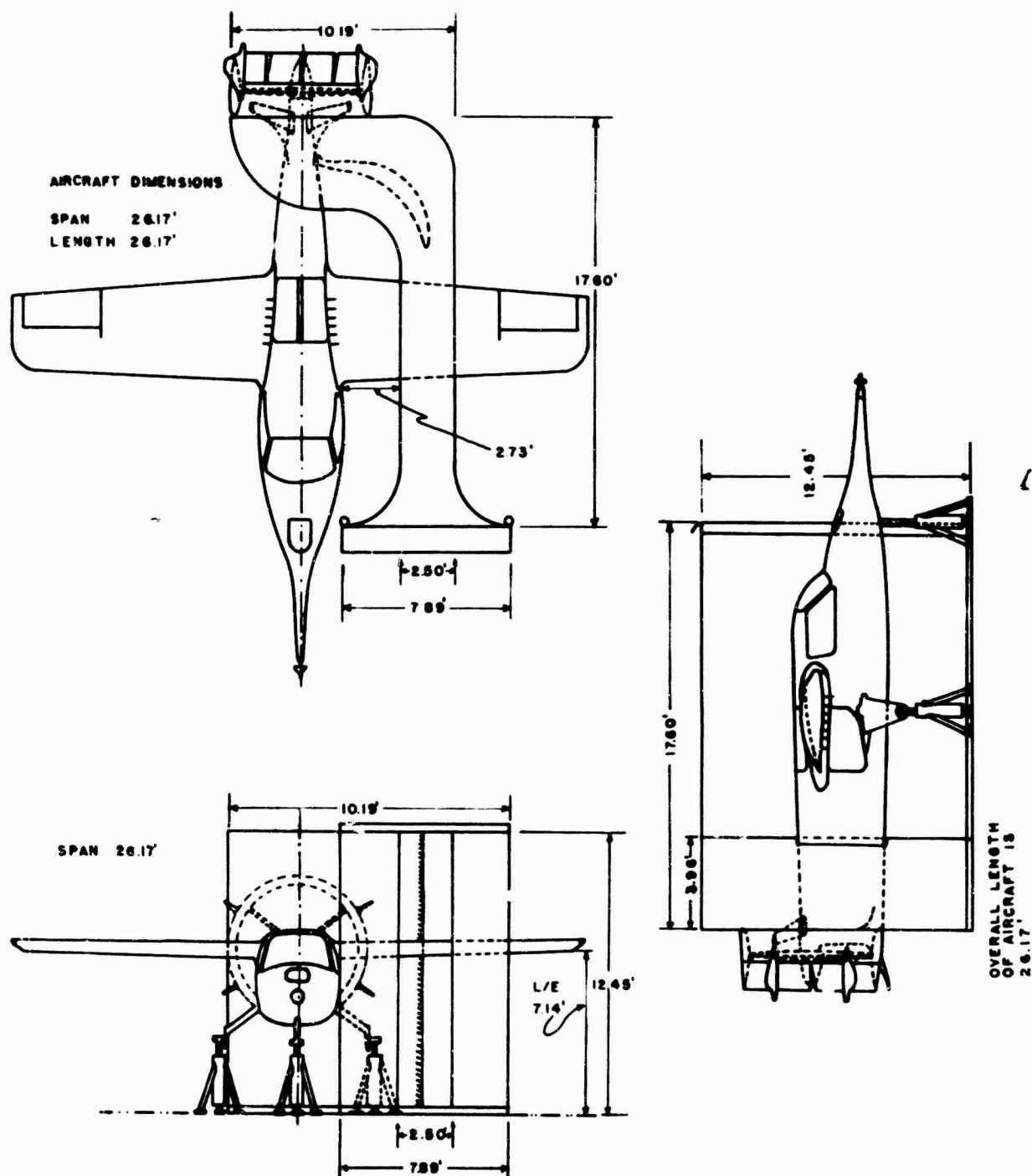


Figure 5. Diagram of the MARVELETTE Wind Tunnel.



Figure 6. Bleed Holes Cut Close to the Side of the Fuselage.

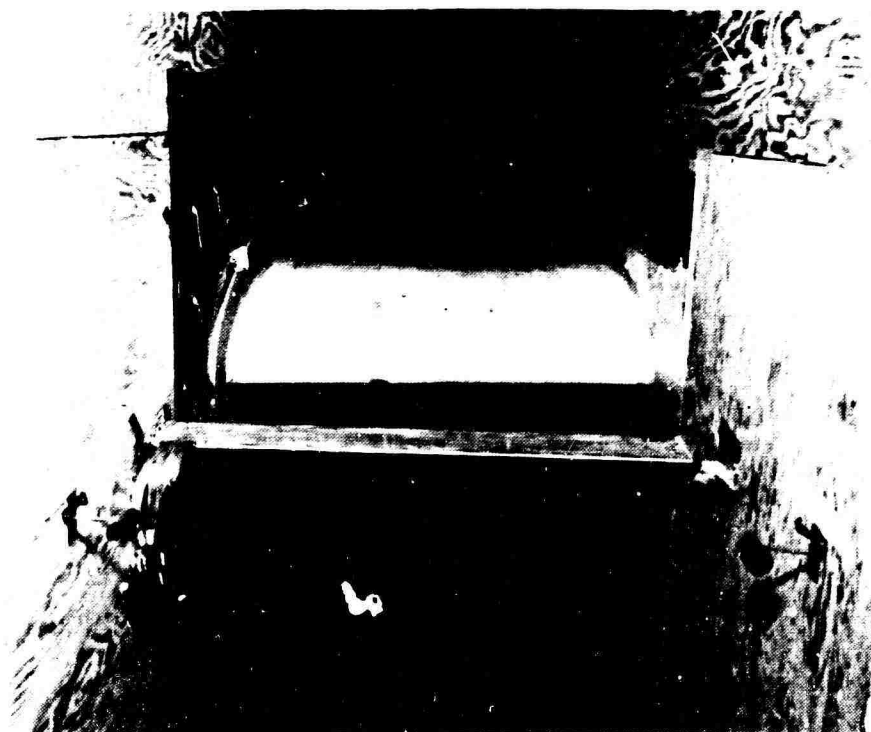


Figure 7. Calibration Rake in the Wind Tunnel.

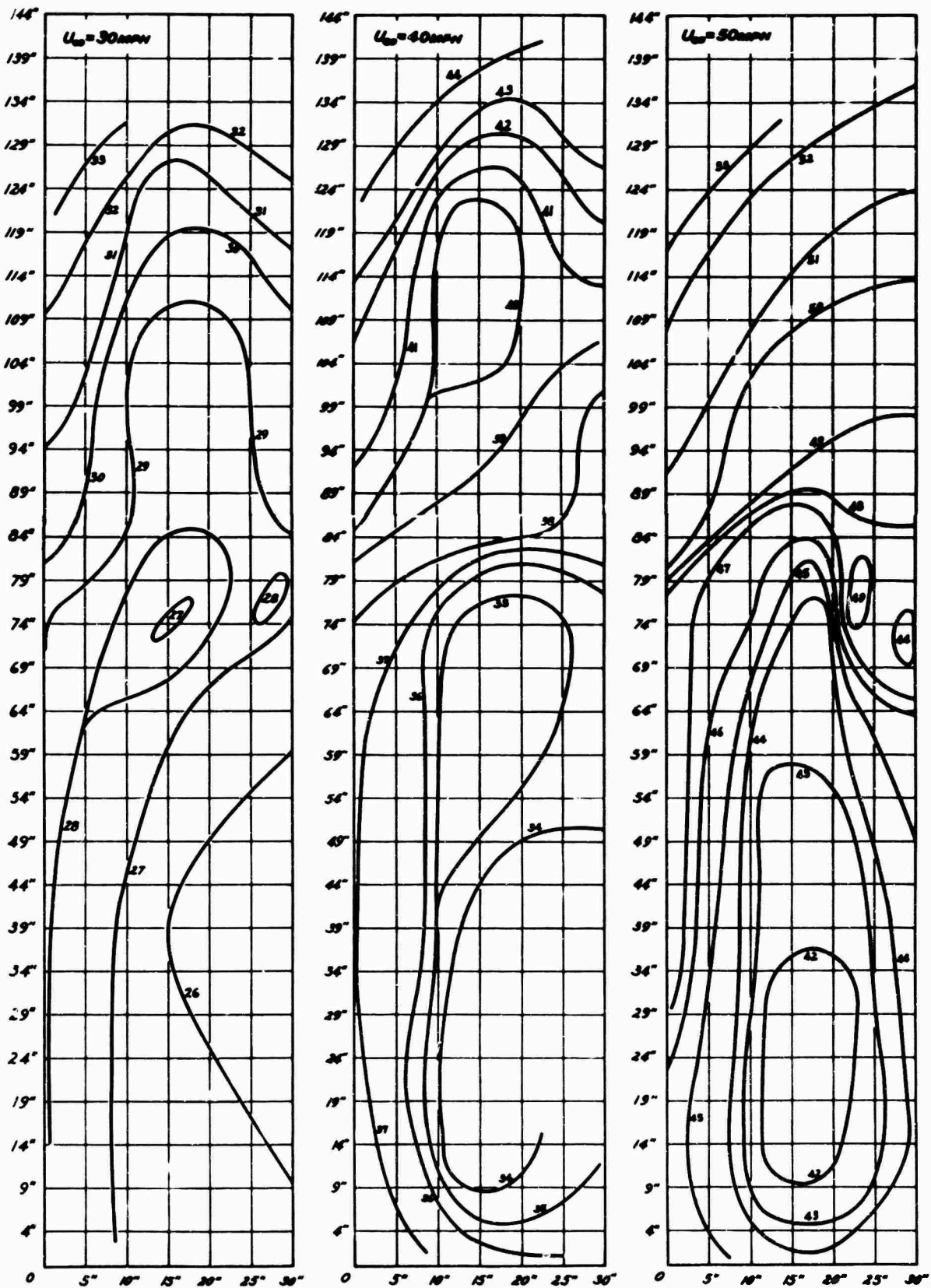


Figure 8. Velocity Distributions in the Wind Tunnel.

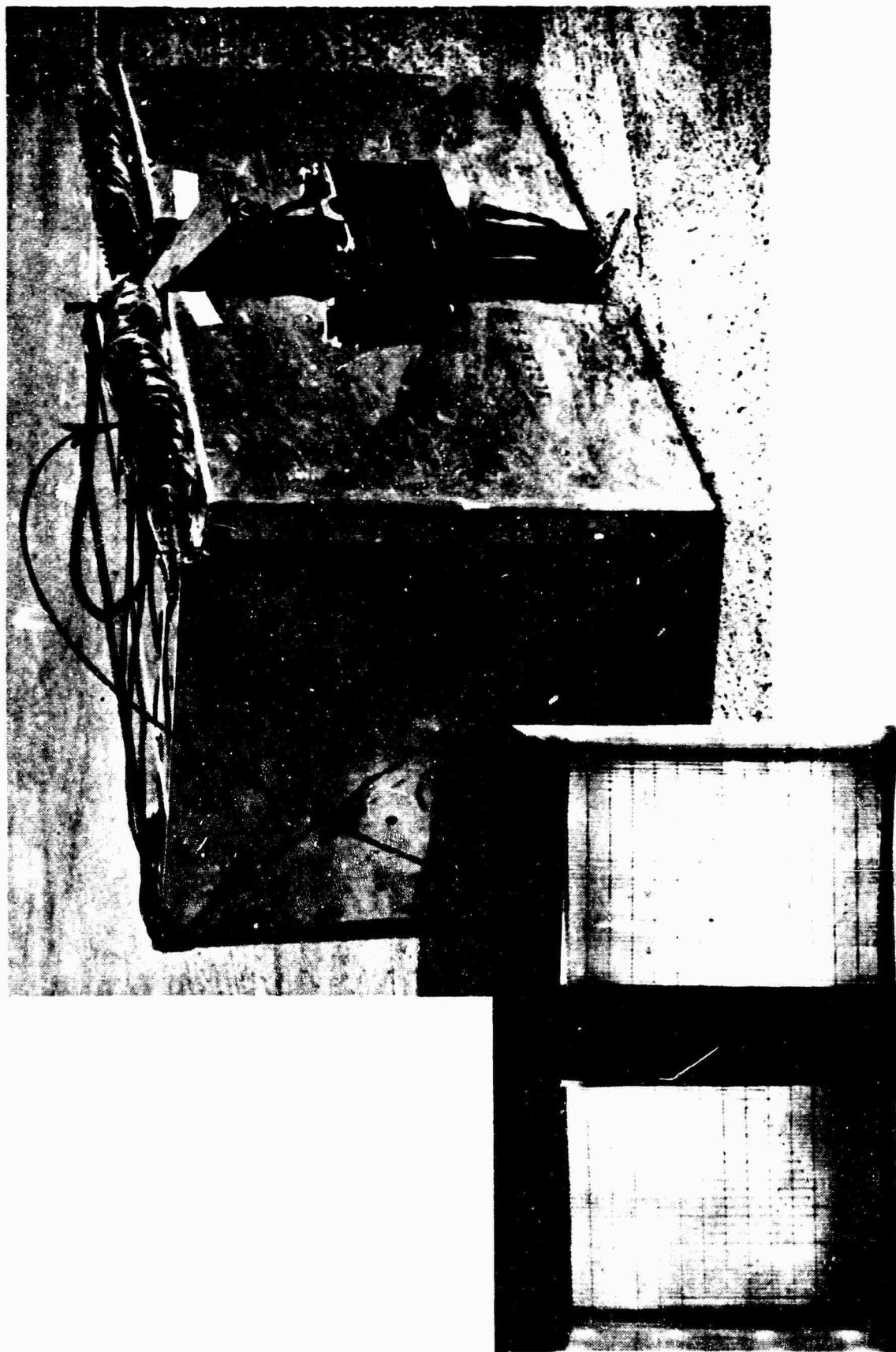


Figure 9. Multitube Water Manometer.

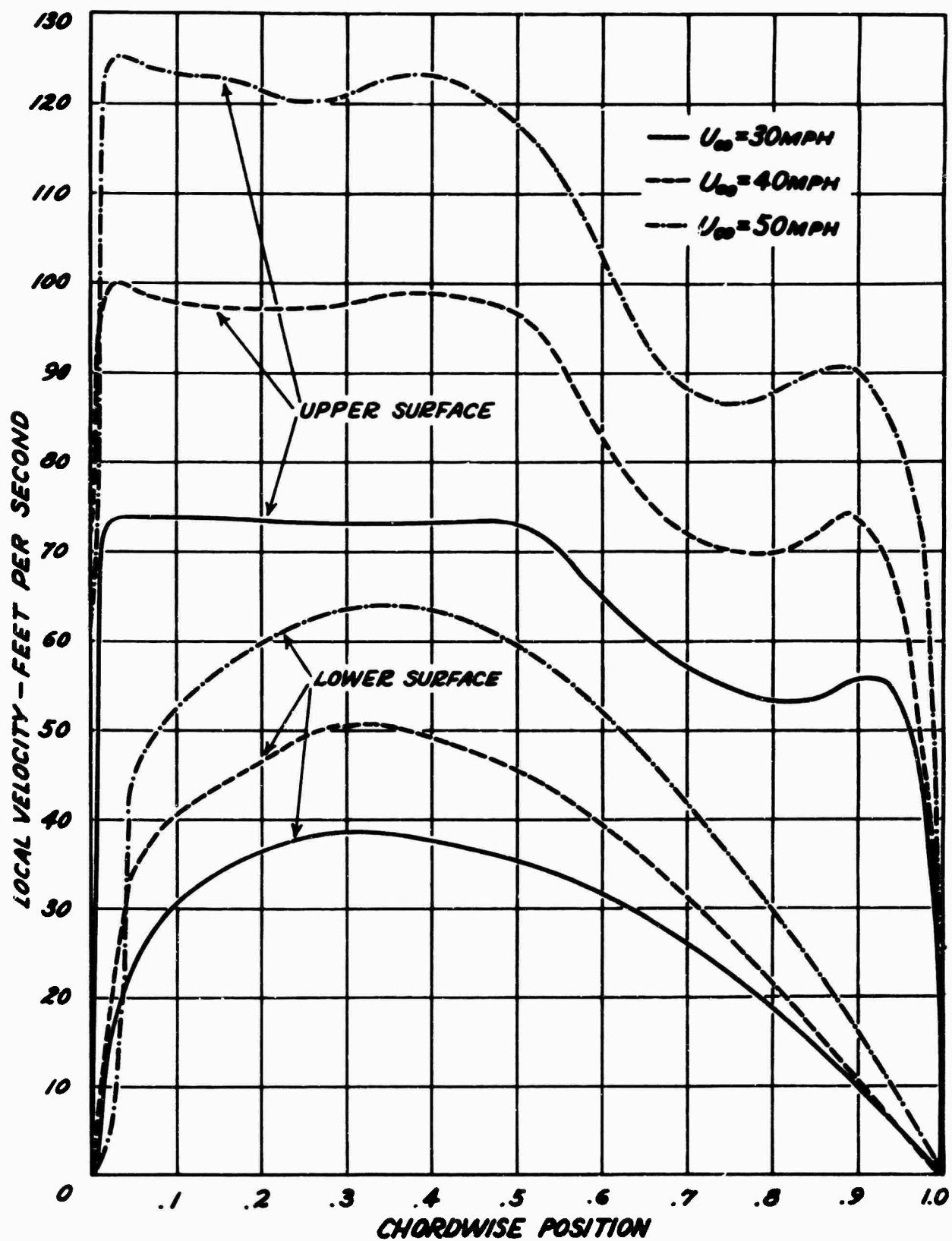


Figure 10. Velocity Distributions on Cambered Airfoil Section.

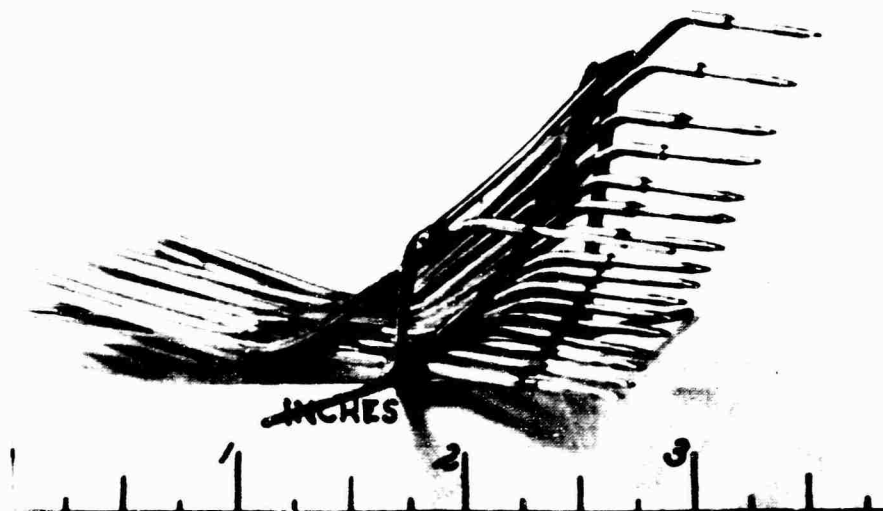


Figure 11. Multitube Boundary Layer Mouse.

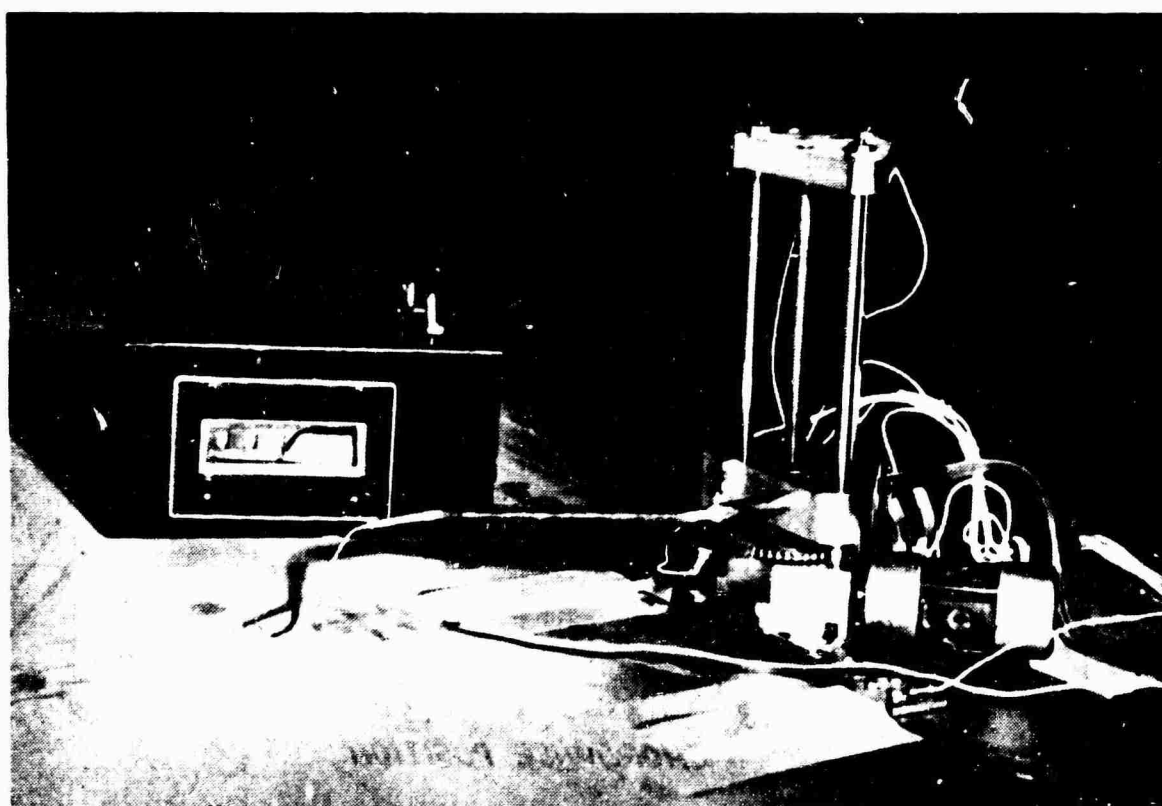


Figure 12. Boundary Layer Pitot-Static Traversing Mechanism.

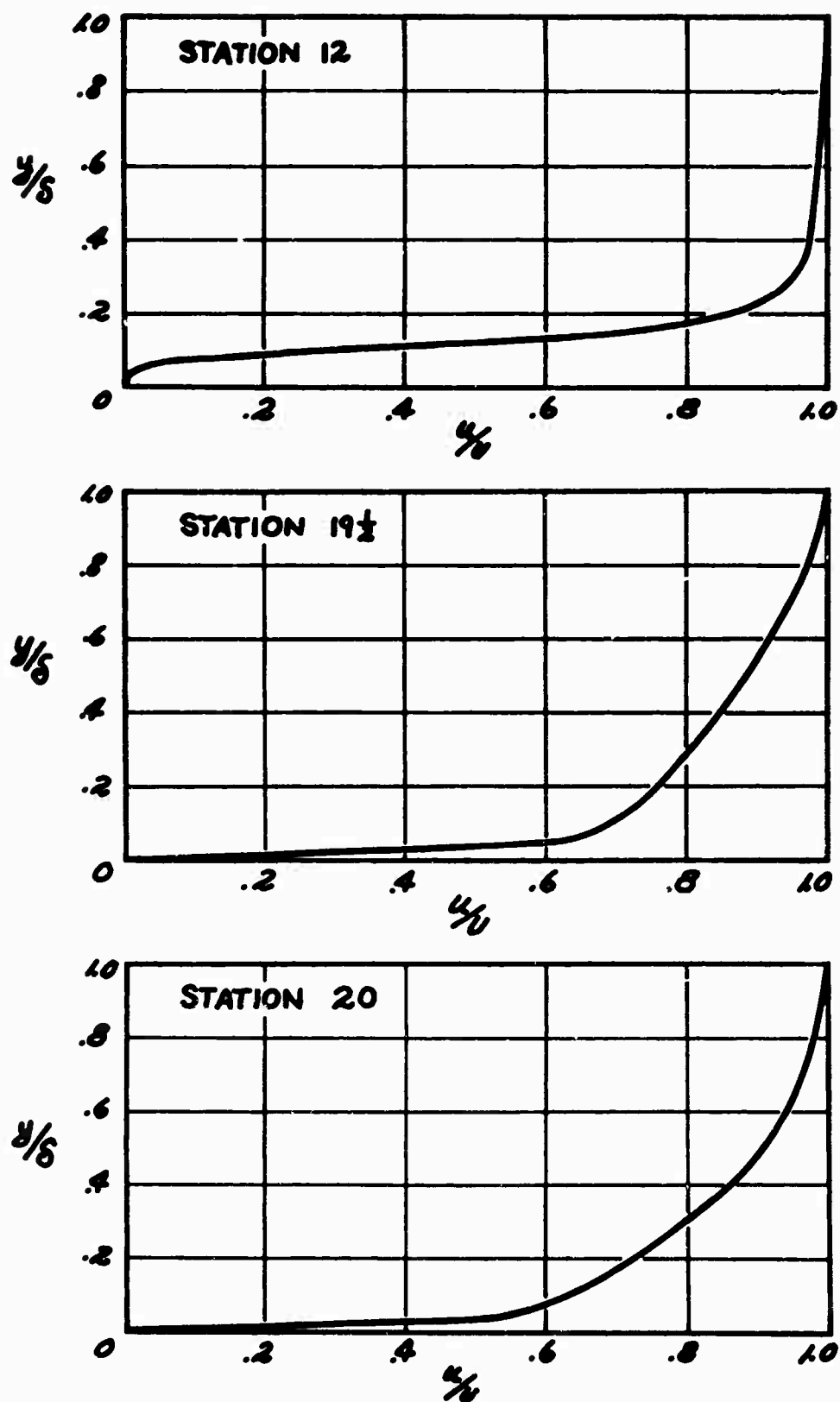


Figure 13. Typical Boundary Layer Velocity Profiles.

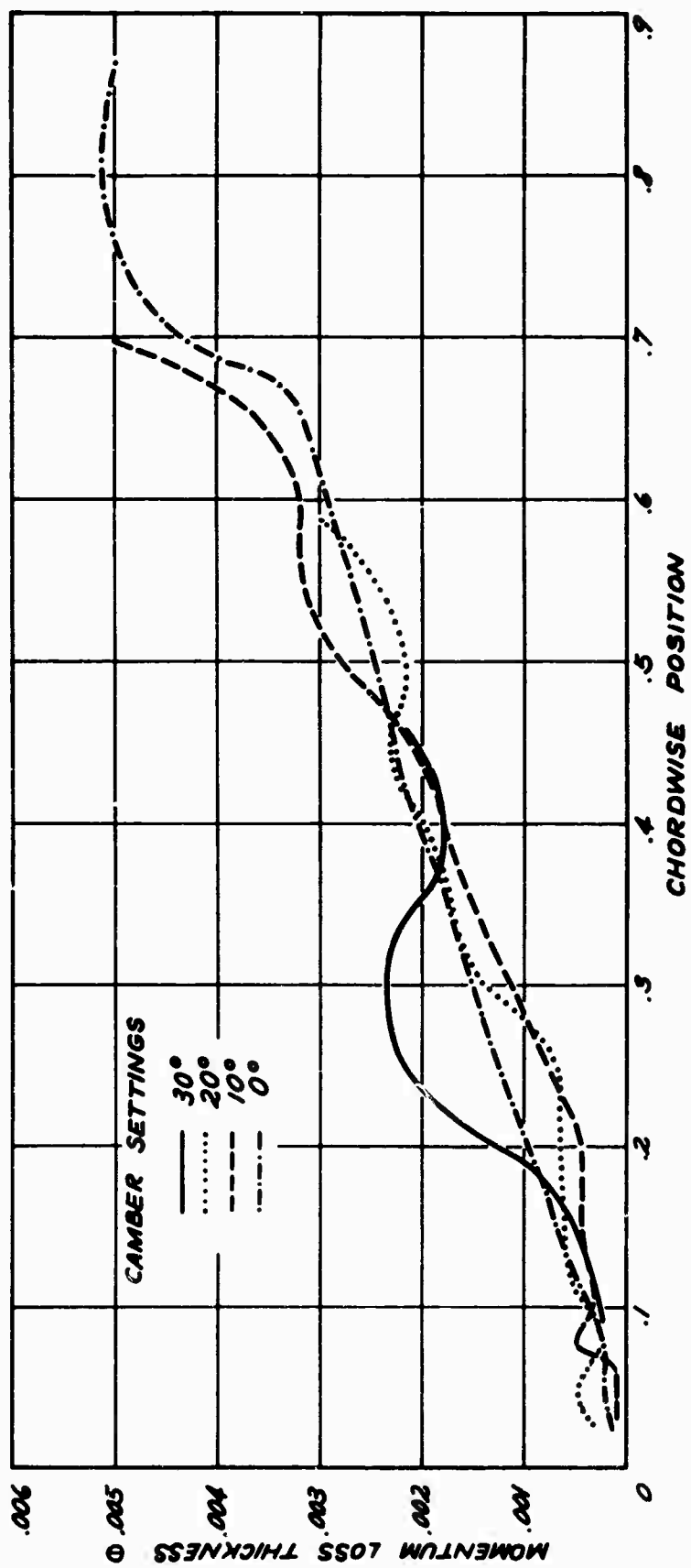


Figure 14. Momentum Loss Thickness Against Chordwise Position for Various Camber Settings.

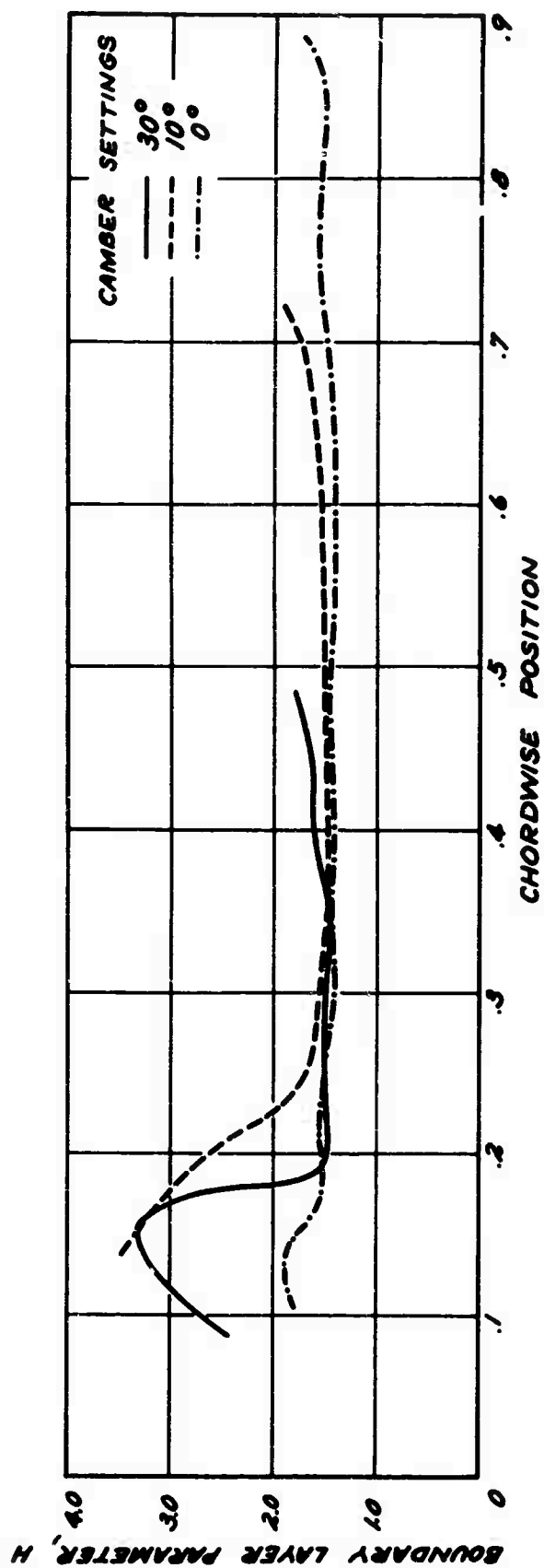


Figure 15. Boundary Layer Parameter H Against Chordwise Position for Various Camber Settings.

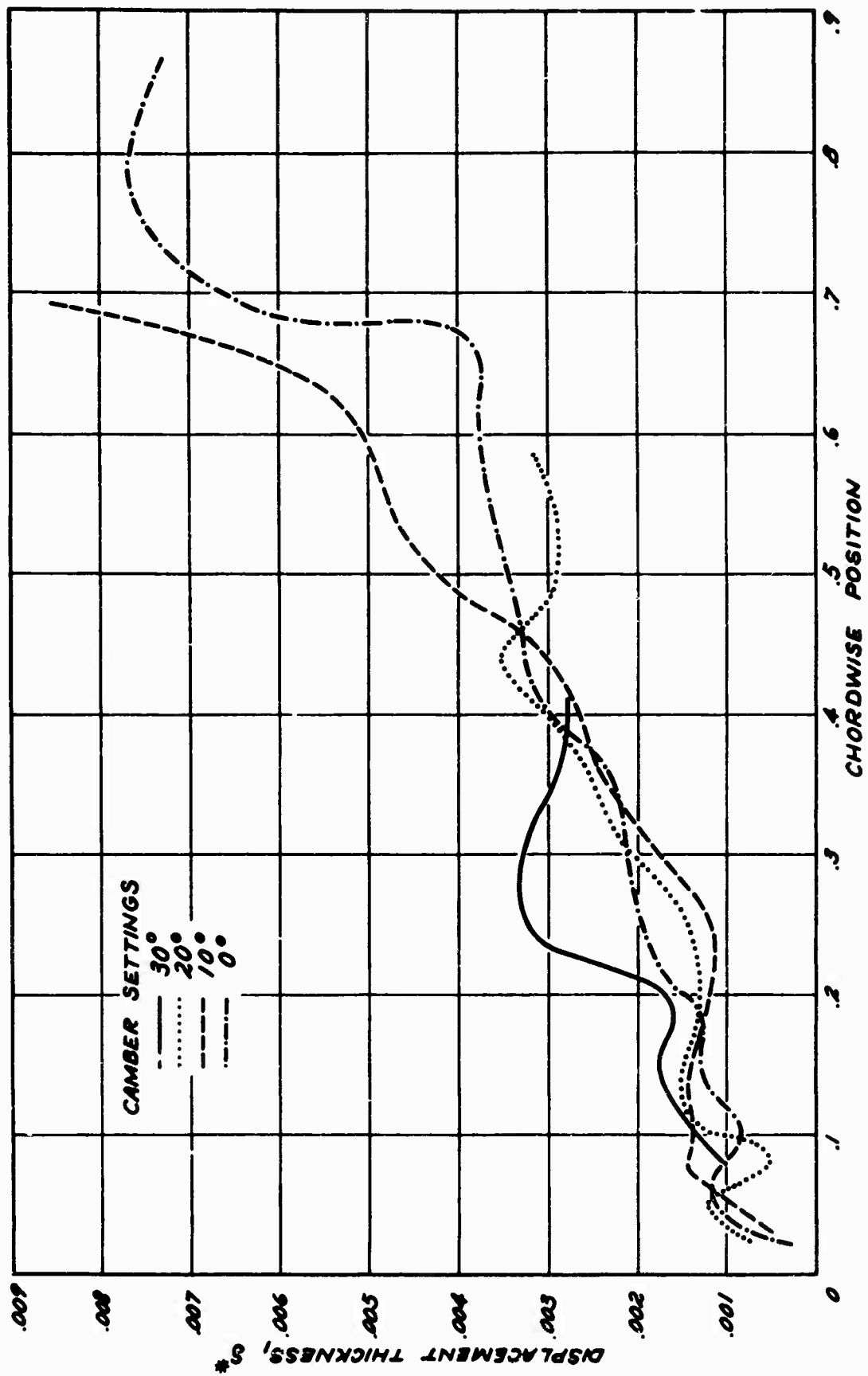


Figure 16. Boundary Layer Displacement Thickness.

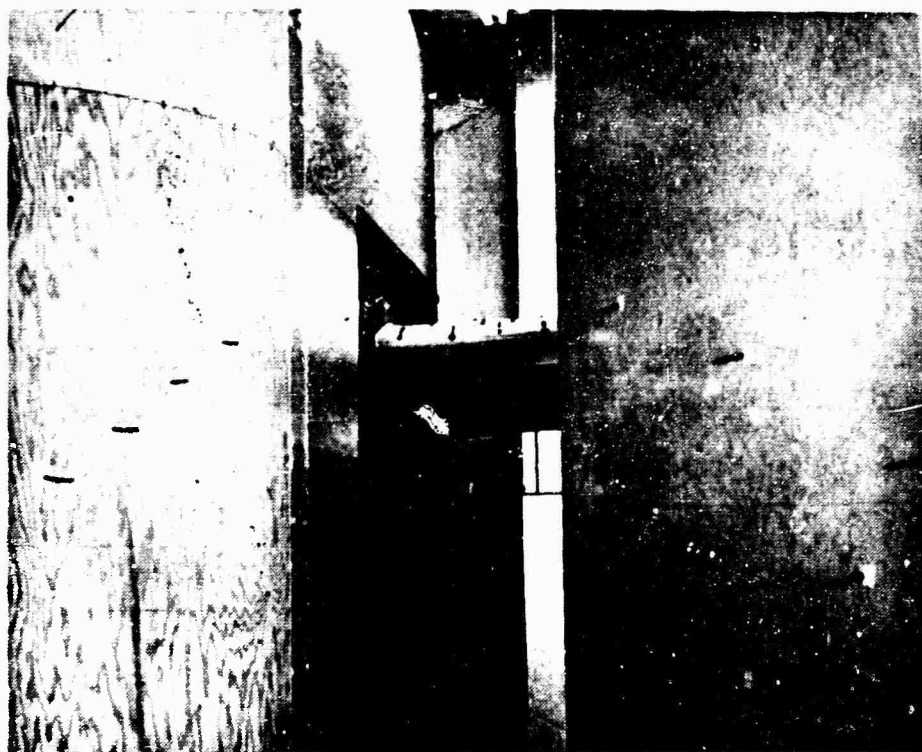


Figure 17. Typical Tuft Photographs of a Test Section,
 $U_{\infty} = 40$ MPH.

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